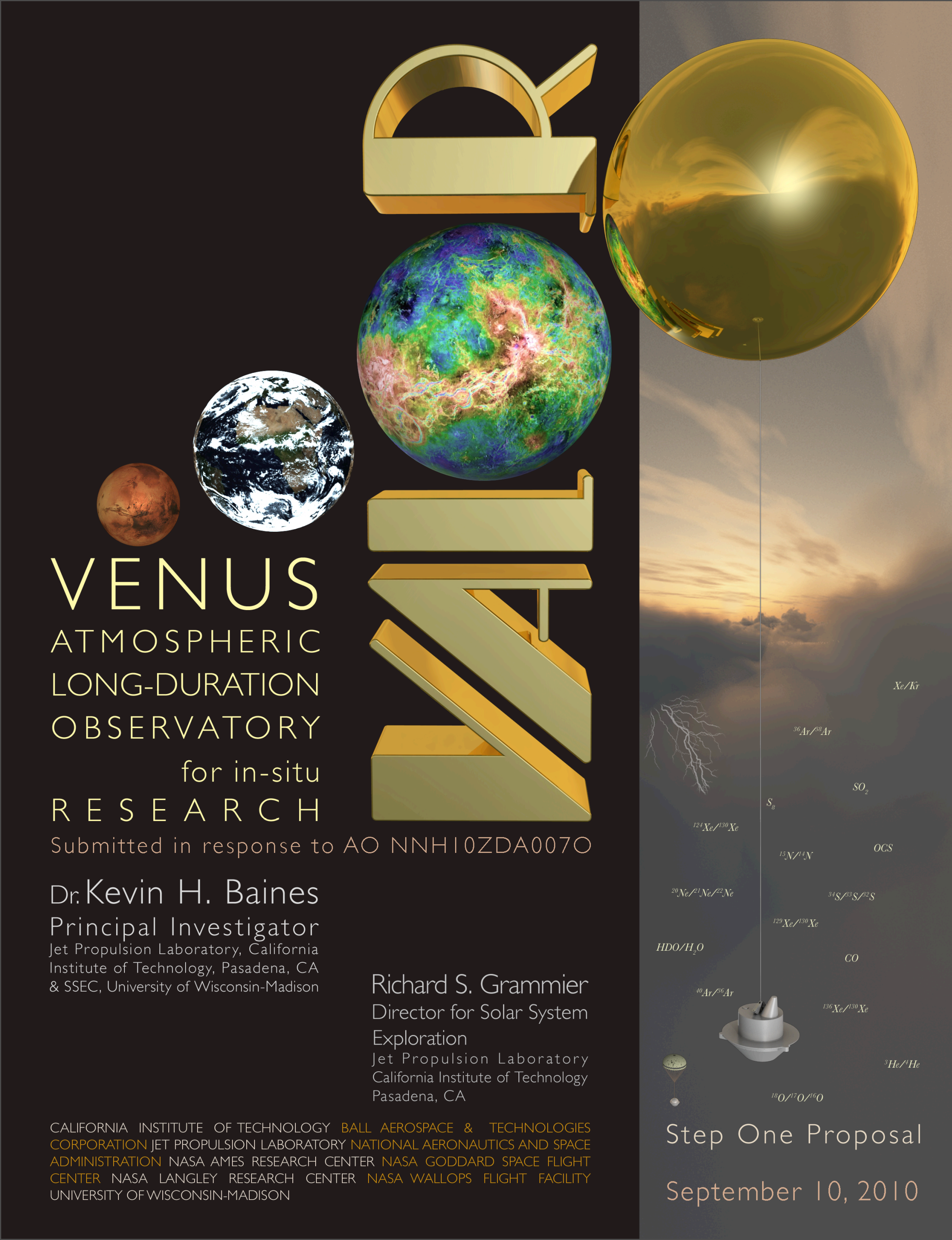

Exploring Venus with Balloons – Science Objectives and Recent Technical Advances

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IPPW-9
Toulouse, France
June 2012

VALOR:
“Experiencing Venus”

A Long-Duration “World Tour” of our Sister World to Explore its

- Origins
- Evolution/History
- Current Processes
  - Circulation, Dynamics
  - Climate
  - Chemistry and
  - Meteorology

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Basic Questions

- Was Venus Ever Like Earth?
  - Oceans?
  - Life?

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Basic Questions
- Was Venus Ever Like Earth?
  - Oceans?
  - Life?

- Why did it Evolve so Differently?
  - Hurricane-Force Winds
  - Hellish Temperatures (900^{o} F, 470^{o} C)
  - Extreme Pressures (Like being 3000 feet underwater)

VALOR
Decadal Study Goals

VALOR Directly Addresses Cross-cutting Themes and Major Questions of The 2011 Decadal Study:

- **Building New Worlds—Understanding Solar System Beginnings**

  What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?

- **Planetary Habitats - Searching for the Requirements for Life**

  Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged?

- **Workings of Solar Systems—Revealing Planetary Processes Through Time.**

  Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?

  How have the myriad chemical and physical processes that shaped the Solar System operated, interacted, and evolved over time?

VALOR
Science Objectives And Instruments

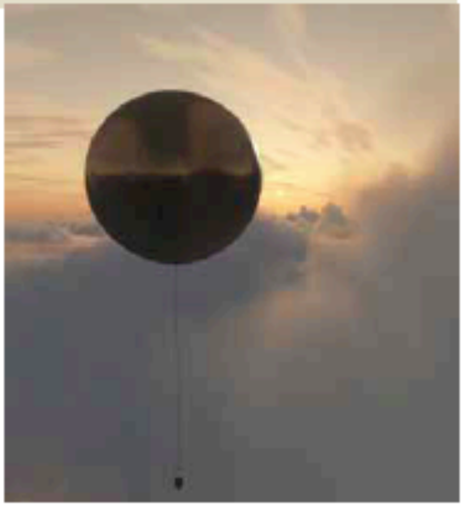
VALOR Seeks to:

- Provide the missing links to a fundamental understanding of the **origin** and **evolution** of both Venus and the other terrestrial planets
- Assess Venus' **climate** and conduct comparative climatology studies between Venus and Earth with respect to greenhouse gases and global climate change
- Elucidate Venus' reactive **chemistry**, including the history of volatile compounds and evidence of present-day volcanism (if any)
- Improve understanding of general atmospheric **circulation and dynamics**, in particular, the phenomenon of super rotation.

Balloon-borne aerostat at 55.5-km altitude	
Instruments	**Measurements**
VMS / TLS (Venus Mass Spectrometer; Tunable Laser Spectrometer)	Abundances of - Noble gases and - isotopes - Chemically-active trace species (SO_2, OCS, CO,H_2O) - Light isotopes (C,H,O, N, S)
VASI (Venus Atmospheric Structure Investigation)	• Pressure • Temperature • Vertical wind • Particle size/density; uv
ART (Aerostat Radio Tracking)	• 3-D winds
LiD (Lightning Detector and Magnetometer)	• Lightning rate/strength • Remnant Magnetism
VEMEX (Venus Microphone Experiment)	• Venus sounds/thunder
VALCAM	• Balloon/cloud

Why Use a Balloon?

Mission Drivers



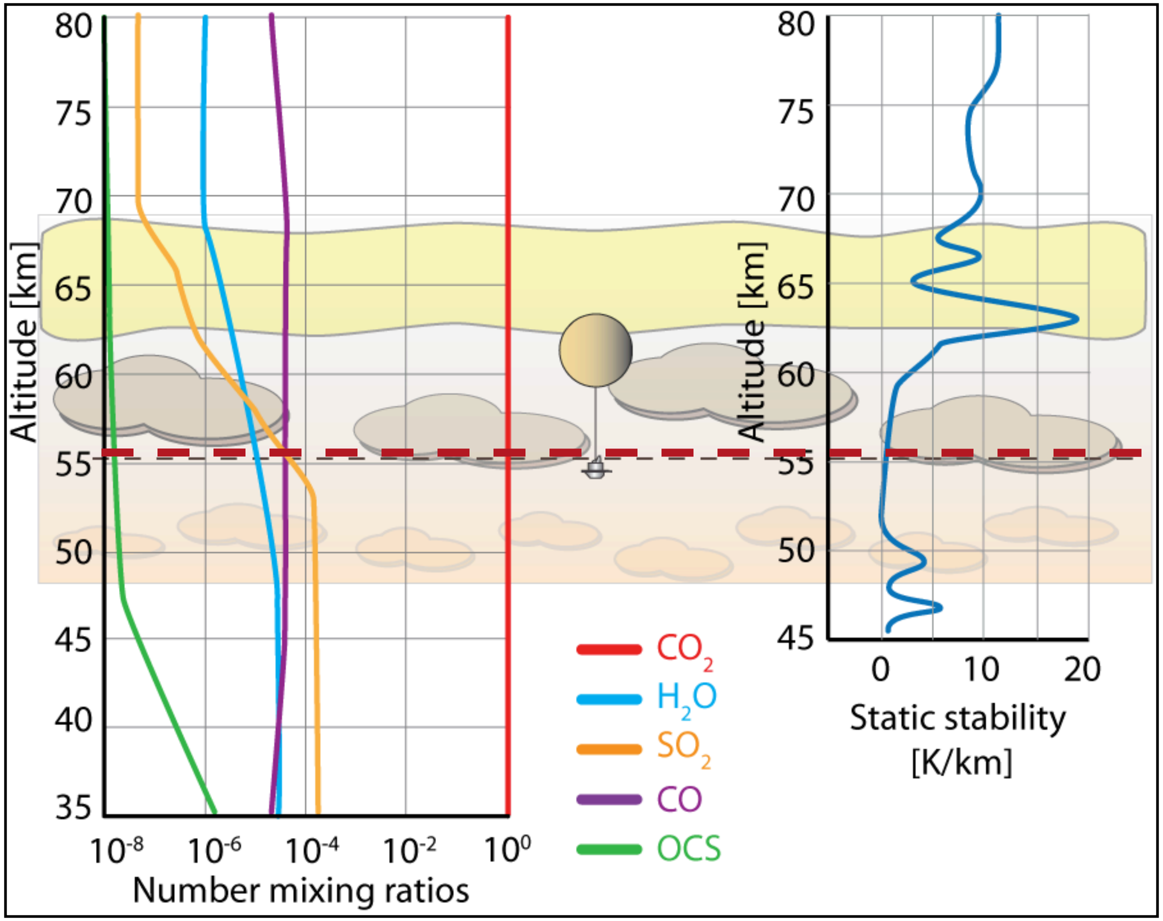
- Understanding the **circulation, dynamics, chemistry, & meteorology** of Venus **requires in-situ mobile platform measurements** of
  - Vertical, zonal (East-West), meridional (poleward) motions and temperatures,
  - Constituent abundances and cloud densities and particle sizes
  - Day & night tracking; front & backside tracking
- Data can only be acquired **with an in-situ mobile platform**
- In situ mobile measurements are key to understanding
  - the **roles of waves** (e.g., gravity, planetary), turbulence, and convective processes in transporting momentum vertically and latitudinally
  - the key pathways of the **sulfur cycle** and its role in producing and maintaining clouds, which regulate the principal heat-absorbing layer in Venus
  - Venus's mysterious global **super-rotation**

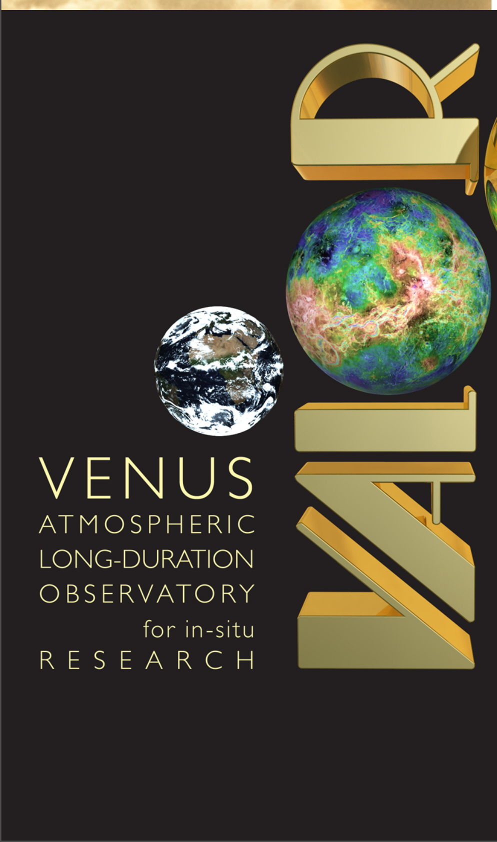
VALOR:

Long-Duration Flight in the Climatologically- and Meteorologically--Interesting Region of the Venusian Skies

Varying Greenhouse Gases

Unstable Atmosphere: Convection and Waves





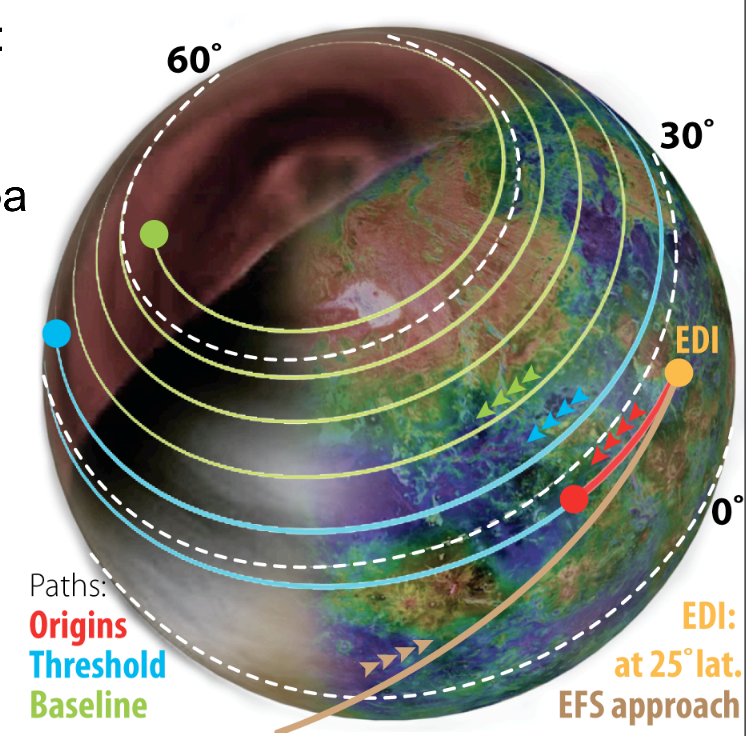
THE VALOR MISSION ARCHITECTURE

- Single, 7.3-m Super-Pressure Balloon, 100 kg Payload

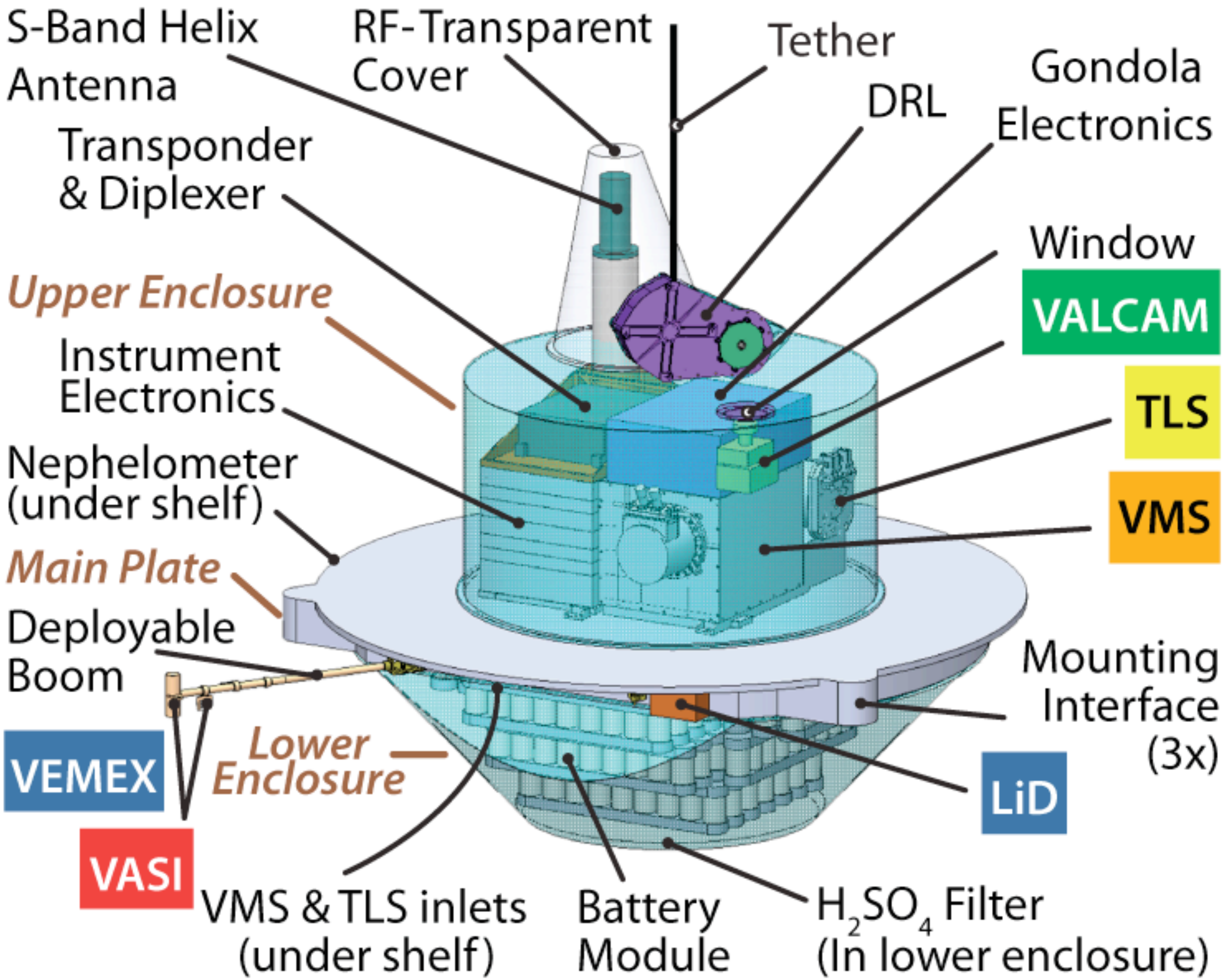
- Nominal (Baseline) Mission:
    - Atmospheric Flight Lasting 24 days
    - Multiple Circumnavigations (~5)
    - Fly from 25^o N. Lat to > 60^o N. Lat
        - Based on Galileo observations of Northern Hemisphere
        - Fly at 55.5 km altitude (mean); 0.5 bar, 24 C

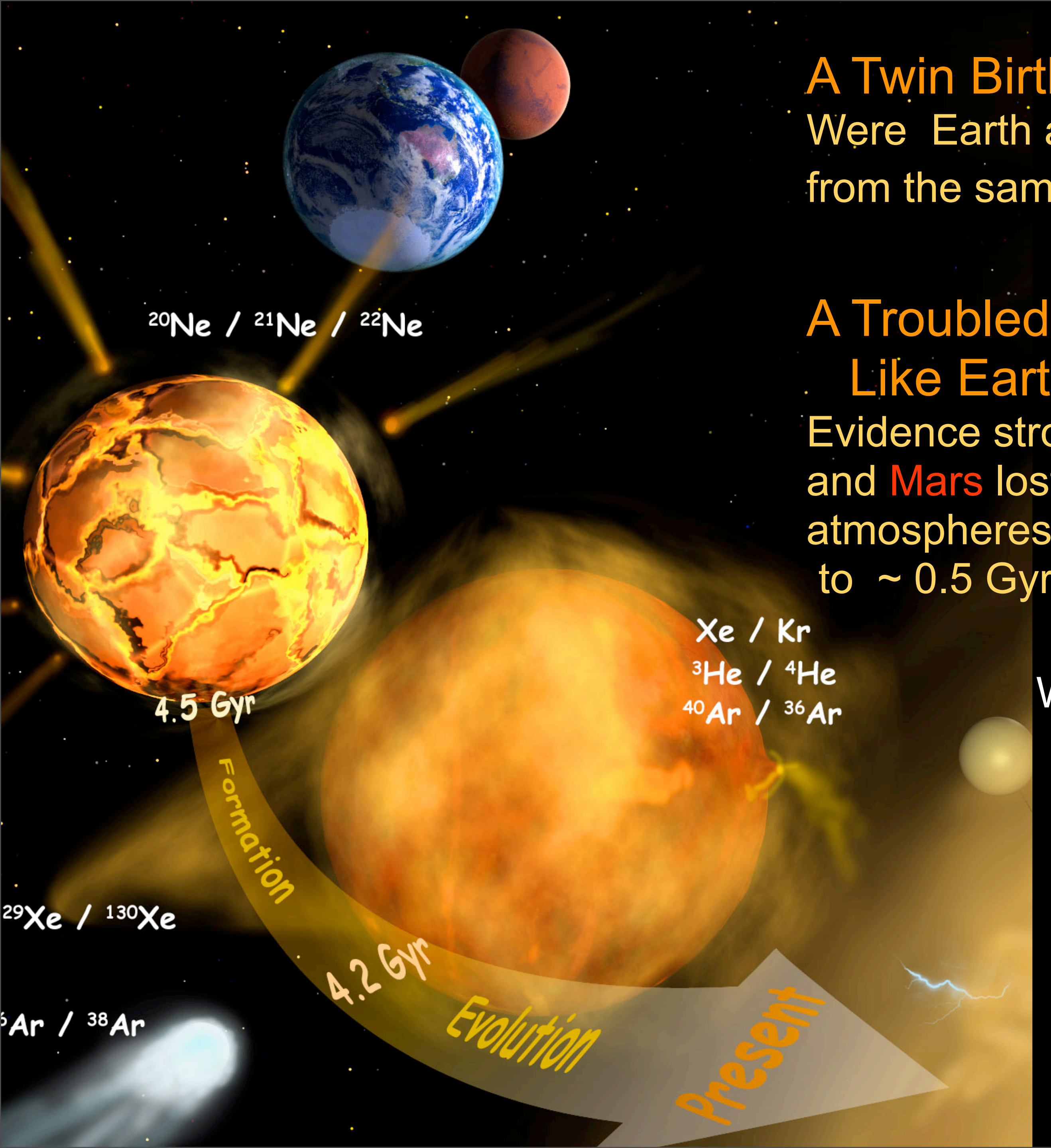
- Back-up (Threshold Mission):
    - Atmospheric Flight:
        - 8 days
        - ~ 1.4 Globa
    - Fly from 25^o N to ~ 30-45^o N Lat

-



VALOR Gondola
Instrument Complement





A Twin Birth of Planets?

Were Earth and Venus formed from the same source?

A Troubled Youth for Venus, Like Earth and Mars?

Evidence strongly suggests that Earth and Mars lost much of their early atmospheres during their first ~ 0.25 to ~ 0.5 Gyr

Venus

- No tell-tale Xe data
- No $^{21}Ne/^{22}Ne$ data
- No $^{3}He/^{4}He$ data

VALOR In-Situ Atmospheric Exploration

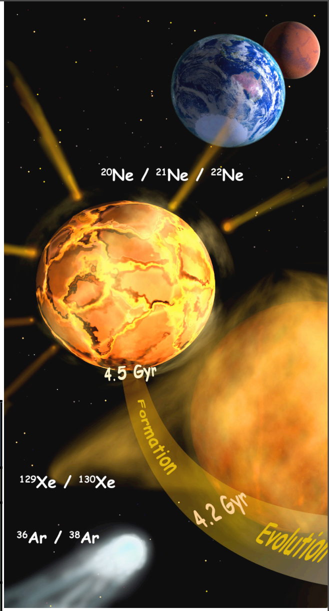
Salient Science Measurements

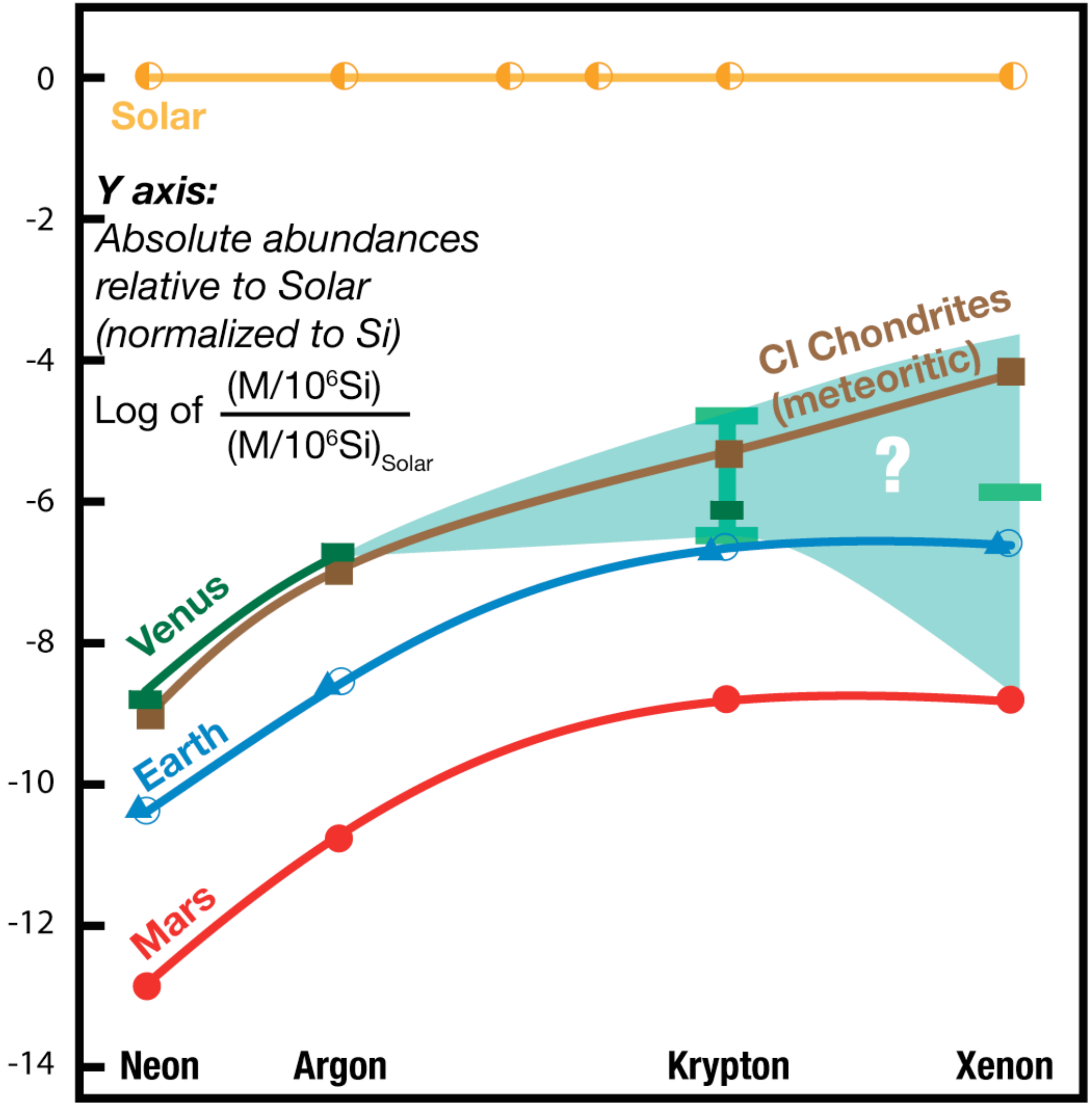
- Noble Gases and Their Isotopes: Formation/Evolution
- Isotopes of Light Gases: Formation/Evolution

Before VALOR

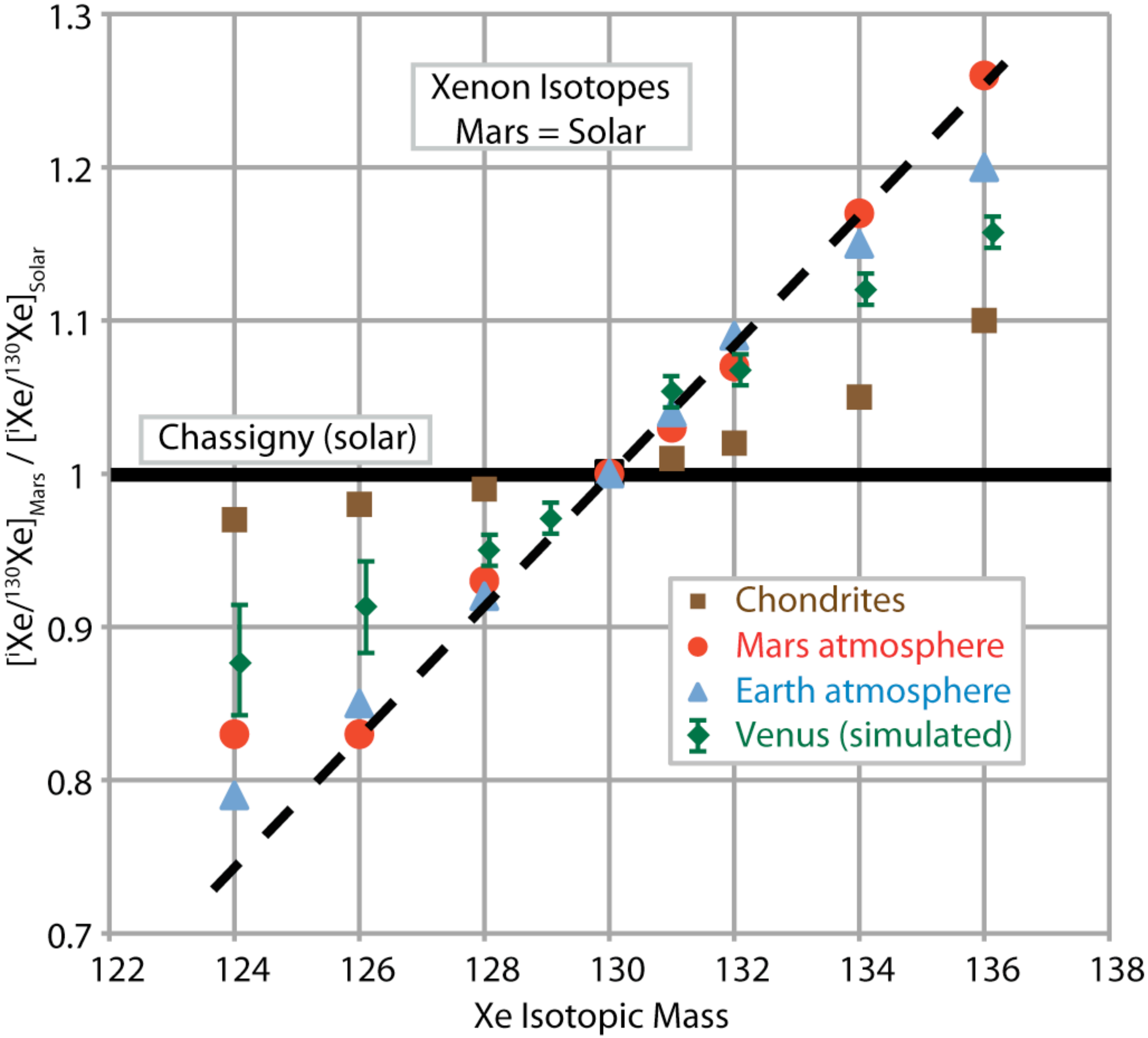
After VALOR

Constituent	Primary Science Objective	Current Measurements	Implied Uncertainty	Required Uncertainty	VMS/ TLS Accuracy
Noble Gases					
^{132}Xe	Origin/evolution of terrestrial planets: Roles of blowoffs, comets, and planetesimals	~1.9 ppb	>200%	10%	10%
^{84}Kr	Origin/evolution: Cold comets as atmospheric gas supplier	0.7 ± 0.35 ppm or 0.05 ± 0.025 ppm	>100% (average)	10%	10%
^{36}Ar	Planetary origin: Roles of comets and planetesimals	31 ± 9 ppm	33%	10%	10%
^{20}Ne	Planetary origin: Earth and Venus, a common kinship?	7 ± 3 ppm	43%	25%	25%
^{4}He	Early evolution: Interior outgassing	12 (+24/-8) ppm	>60%	5%	5%
Noble Gas Isotopic ratios					
$^{129}Xe/^{130}Xe$	Early evolution: Large atmospheric blow-off	~3	>100%	1%	1%
$^{136}Xe/^{130}Xe$	Origin/evolution: U-Xe hypothesis	~1	>100%	1%	1%
$^{40}Ar/^{36}Ar$	Early history: Interior outgassing	1.03 ± 0.04 or 1.19 ± 0.07	12% (average)	2%	1%
$^{36}Ar/^{38}Ar$	Late formation: Large impact	5.56 ± 0.62 or 5.08 ± 0.05	12% (average)	2%	1%
$^{21}Ne/^{22}Ne$	Earth/Venus origins: Twin planet hypothesis	<0.067	>200%	5%	1%
$^{20}Ne/^{22}Ne$	Earth/Venus origins: Hydrodynamic escape	11.8 ± 0.7	6%	5%	5%
$^{3}He/^{4}He$	Evolution: Impact of solar wind	$< 3 \times 10^{-4}$	>200%	10%	10%
Light-Element Isotopic Ratios					
HDO/H_2O	Atmospheric loss, past/current volcanic activity	0.019 ± 0.006	32%	3%	0.2%
$^{15}N/^{14}N$	Atmospheric loss since planetary formation	0.0037 ± 0.008	22%	3%	2%
$^{17}O/^{16}O$	Planetary origin: Earth and Venus, a common kinship?			0.01%	0.01%
$^{33}S/^{32}S$	Past/current volcanic activity, magmatic composition	~ 0.0079		1%	0.2%

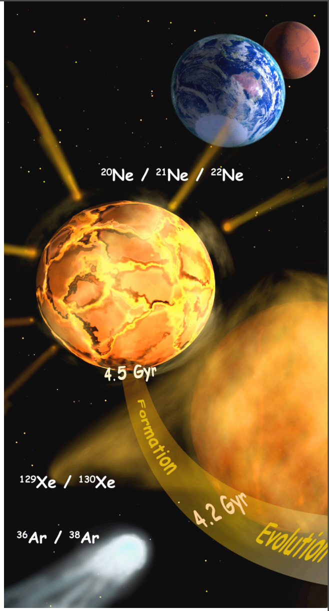




[after Pepin, *Icarus* **92**, 2-79, 1991]


Xenon Isotopes
Mars = Solar
Chassigny (solar)
Chondrites
Mars atmosphere
Earth atmosphere
Venus (simulated)
1.3
1.2
1.1
1
0.9
0.8
0.7
122
124
126
128
130
132
134
136
138
Xe Isotopic Mass
[^{i}Xe/^{130}Xe]$_{Mars}$ / [^{i}Xe/^{130}Xe]$_{Solar}$

VALOR *In-Situ* Atmospheric Exploration

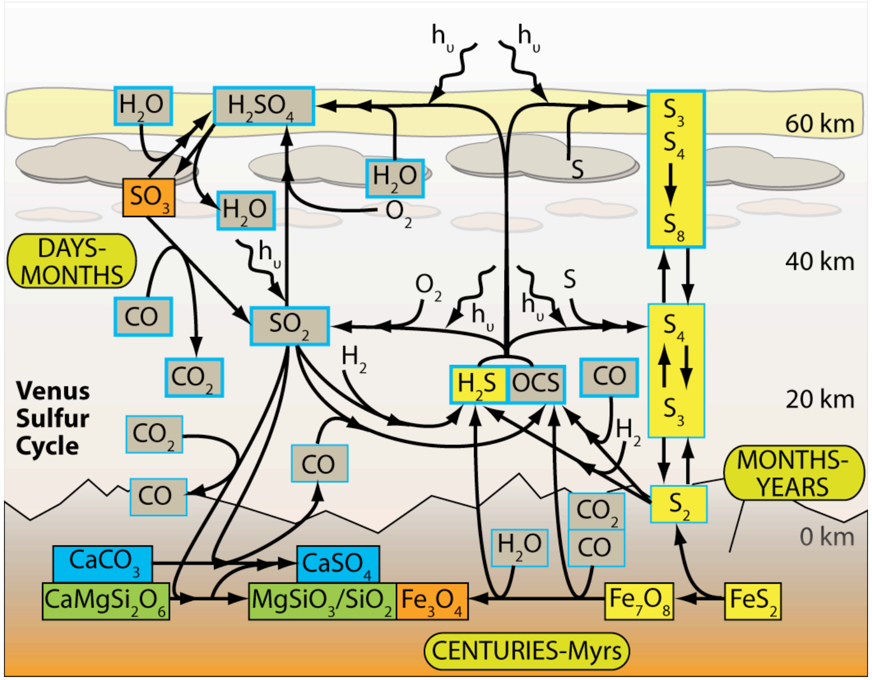


Salient Science Measurements

- Noble Gases and Their Isotopes: Planet Origin/Evolution

- Isotopes of Light Gases: Planet Origin/Evolution

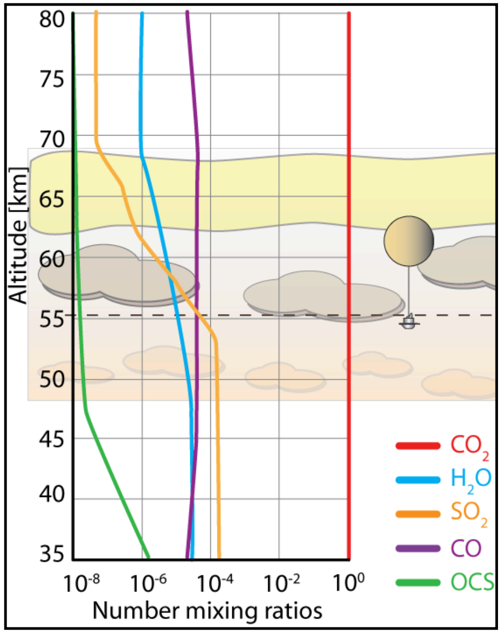
- Precise Abundances (<0.01-3%, generally) and
  Detailed Vertical Distributions
  of Key Reactive Gases : Chemistry/Meteorology



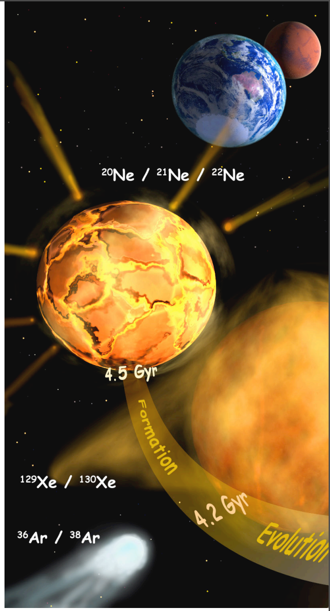
Constituent	Expected Value	Desired Measurement Accuracy	MS accuracy	TLS Accuracy
H_2O	30 ± 15 ppm	0.1	0.25	**0.03**
CO	33 ± 12 ppm	0.01	N/A	**0.0001**
OCS	4.4 ± 4 ppm	0.01	0.25	**0.00001**
SO_2	150 ± 30 ppm	0.1	0.1	**<0.01%**
H_2S	3 ± 2 ppm	0.25	**0.25**	N/A
S_8	<30 ppb	0.5	**1 ppb**	/NA

Sulfuric Cloud Meteorology: Coupled Dynamics and Photochemistry

- Sulfur-cyle H_2SO_4 clouds depend on amounts of UV light, water, and SO_2 .
  - UV light depends on time of day
  - Water variable at cloud base (Tsang *et al*, 2010)
  - SO_2 : Expected to vary by > 200% over 2 km of VALOR bobbing under equilibrium conditions
    - Vertical and horizontal dynamics can dramatically vary SO_2 supply, and thus H_2SO_4 cloud formation



VALOR *In-Situ* Atmospheric Exploration



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- Mean Zonal and Tidal Flow: Circulation/Meteorology

- Meridional Character of 3-D Circulation/Meteorology
  - Momentum and Heat Transfer; Hadley Cells

Venus Atmospheric Circulation: MAJOR Observational Deficiencies

- I. *The planet wide average flow is not known at any vertical level for any latitude*

  – Latitude-longitude structure of the cloud tracked winds available mostly on the dayside at mostly one level ~ 67-70 km and a few observations (Galileo SSI) at ~ 61 km for only about 6-8 hours of local solar time.

  – Nightside cloud-tracked winds from VeX/VIRTIS or ground based observations are at a different level than the dayside cloud-tracked winds

  – Lack of knowledge of the mean zonal component means that the latitudinal transport of heat and momentum can not be evaluated

  (I.e, knowledge of u'v' requires knowledge of mean u to compute it)

Venus Atmospheric Circulation: MAJOR Observational Deficiencies

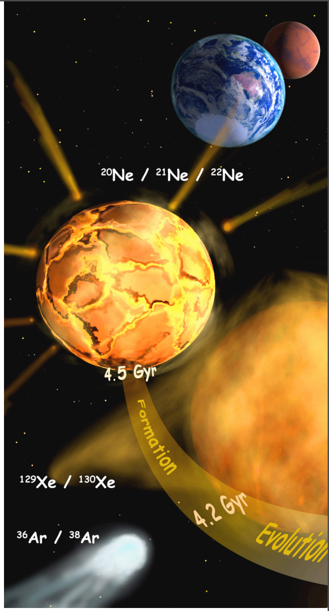
II. *Thermal tides are likely very important in determining the vertical momentum transport in and below the cloud layer*

- Latitudinal transport by waves are indicated in GCMs, but the detailed structure differs from model to model.

- Models are not very mature yet and need better observations for comparisons

- NEXT TO THE MEAN ZONAL FLOW, THERMAL TIDE CHARACTERISTICS ARE THE MOST IMPORTANT MISSING INGREDIENTS FOR UNDERSTANDING GLOBAL CIRCULATION

VALOR *In-Situ* Atmospheric Exploration



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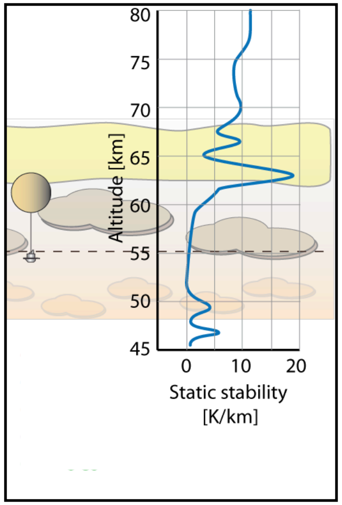
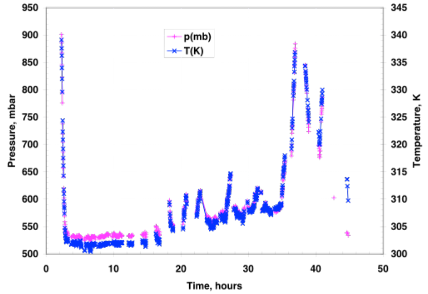
- Vertical Character of Dynamics/Circulation á la VEGA Balloons
  - Gravity Waves
  - Convection, Turbulence
  - Hadley Cell: Latitudinal Boundaries

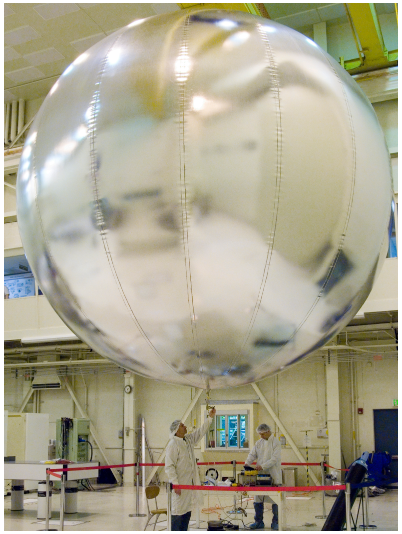




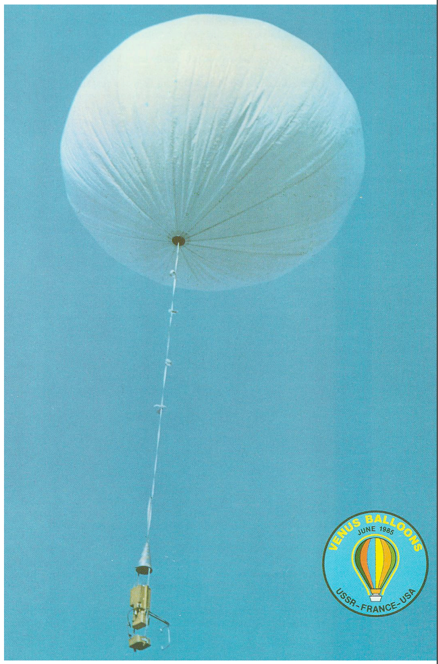
VALOR: Riding the Waves While Circumnavigating Venus

Vertical motions are unknown at Venus except
for Exciting 2-day VEGA Experience

- What are the Roles of Convection, Waves, in Transporting Heat, Momentum, Producing Hurricane-Force Global Super-Rotating Winds?



VALOR Balloon



VEGA Balloon

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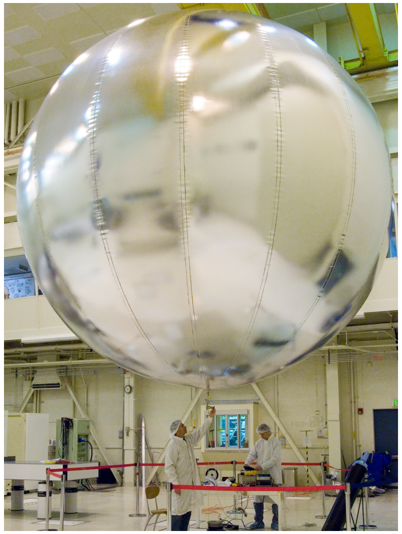
- What are the Roles of Convection, Waves, in Transporting Heat, Momentum, Producing Hurricane-Force Global Super-Rotating Winds?

VEGA regularly “bobbed” vertically ~ 3 km riding gravity waves

VALOR will “bob” ~ 1 km

- Will measure vertical motion and wave characteristics over all times-of-day, longitudes, and many types of terrain
  - Waves vs Convection

VALOR Will Measure, Directly, 3-D Winds at High Temporal and Spatial Resolution Over all Longitides from Temperate to Polar Latitudes



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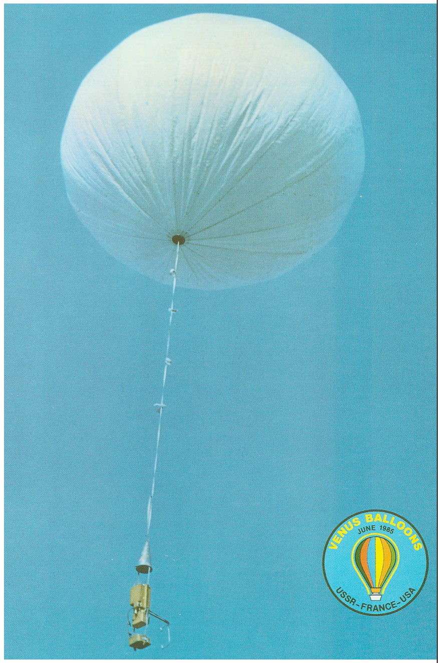
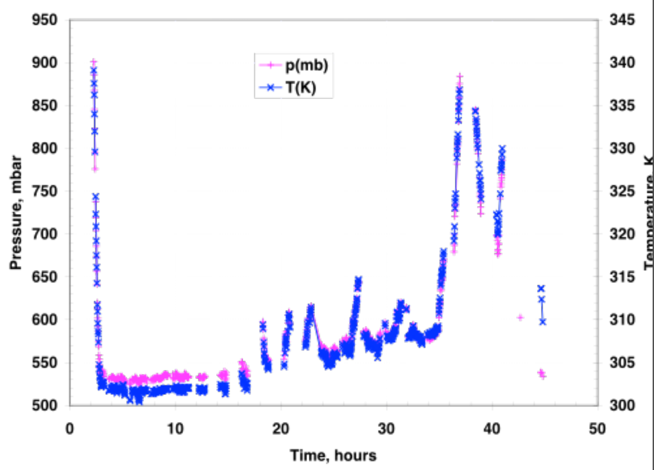


VEGA Balloon



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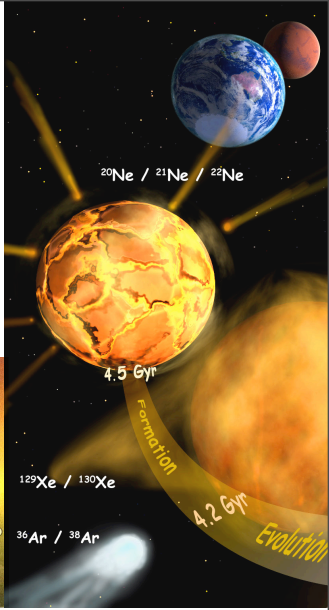
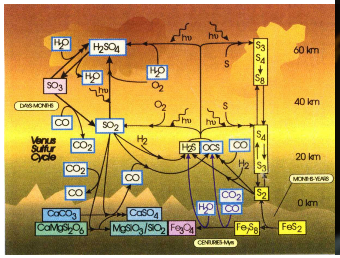
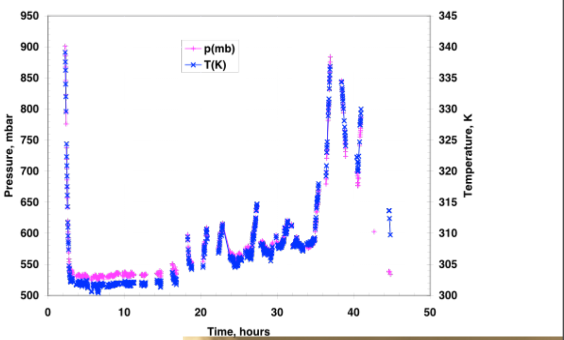
  - Convection, Turbulence
  - Hadley Cell: Latitudinal Boundaries

- Coupled Dynamics/Chemistry of Cloud Evolution Climate
  - Simultaneous Measurements of Parent Gas Abundances, Cloud Number Density and Particle size, Updrafts/Downdrafts, Convection
  - Clear Measurements of Frequency and Strength of Lightning Sampled over all Longitudes

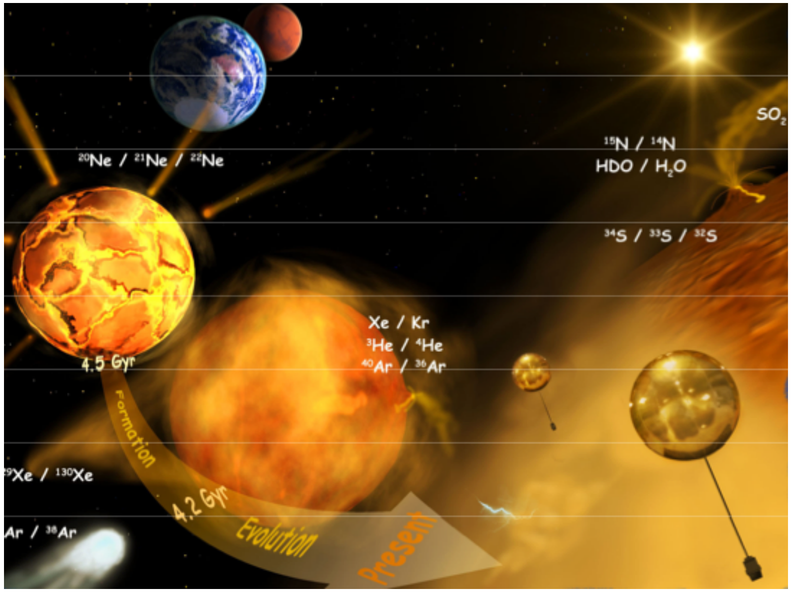






Summary

VALOR's Intensive *in-situ*, Global-Scale Exploration of the Venus Atmosphere is the Next Step for Understanding the Origin, Evolution, Circulation, Meteorology and Climate of our Sister World



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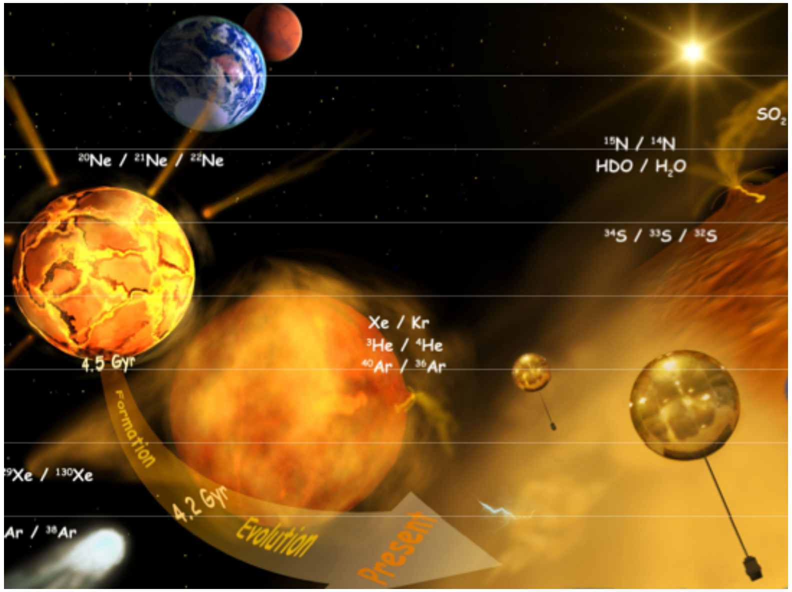
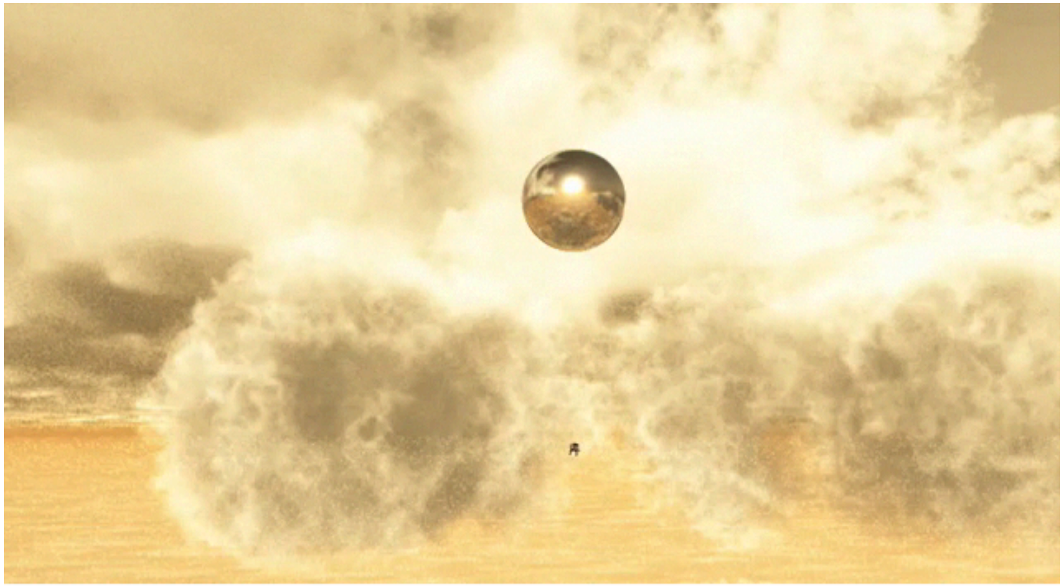




Balloon Technology Overview

- JPL has been working on the balloon technology development since 2005 with its partners ILC Dover (manufacturer) and NASA Wallops.
- We use a spherical superpressure balloon design to achieve 1+ month flights at a ~55 km altitude at Venus.
- Substantial progress has been achieved during that time including:
  - Fabrication and testing of two 5.5 m diameter prototype balloons.
  - Dozens of laboratory tests of material coupons for mechanical, thermal, chemical and optical property characterization.
  - A successful aerial deployment and inflation flight experiment.

5.5 m prototype balloon

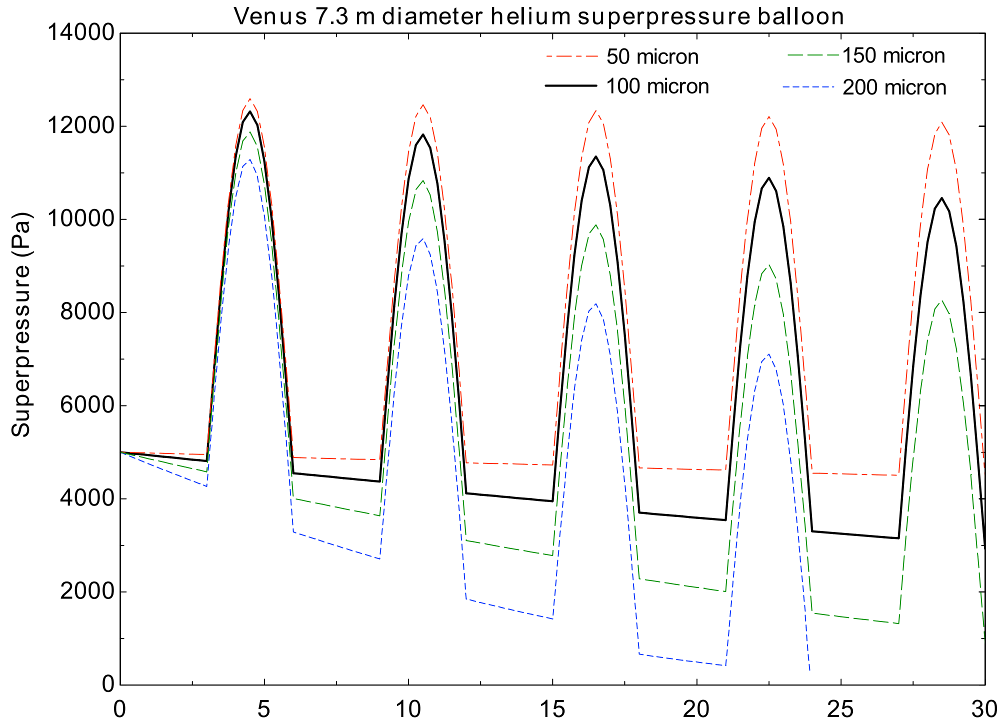
Aerial deployment and inflation test

Recent Technology Focus: Balloon Lifetime

- The work to date builds a strong case that we can fabricate a balloon that can survive the test, storage, and aerial deployment and inflation stages of the mission.
- A key remaining issue is assessing the likelihood that the desired 1+ month mission will be achieved.
- The key threat to mission lifetime after surviving deployment and inflation is gas leakage and/or acid penetration through small pinhole defects created by the folding, deployment or inflation processes.
- There are two aspects to this problem:
  1. Will pinholes be formed?
  2. If they are formed, what is the effect on mission lifetime?
- We have done many severe folding tests on the balloon material and have never been able to create a hole in the protective Teflon layer that allowed acid to penetrate (or gas to escape).
  – But further leakage tests still need to be done after deployment and inflation (the prior test focused on gross structural survival, not leakage).
- Our most recent work has focused on Question #2.

Pinhole Effects

- Calculations indicate that a single pinhole between 150 and 200 μm will leak enough helium gas to result in a < 1 month mission (see graph).
- We have already demonstrated pinhole-free performance in the lab for 1 month.
  - Balloon was fabricated, packaged, shipped, unfolded and inflated in the lab at JPL.
- The question of acid penetration is focused on pinholes < 150 μm in size
  - Anything bigger is already a failure from the point of view of helium loss.



Example of highly wrinkled material sample that does not fail a sulfuric acid exposure test.

Deliberate Pinhole Experiments

- We are in the middle of a series of experiments in which we deliberately make a pinhole in the balloon material and examine how much damage is done over time from sulfuric acid penetration.
- Tentative results with an 80 μm diameter hole indicate that virtually <u>no</u> sulfuric acid can penetrate against the escaping flow of gas.
- Even if there is no gas flow (zero pressure balloon), acid enters the hole <u>very</u> slowly:
  - The thin Aluminum layer under the Teflon dissolves at a rate of ~ 1 mm/day. But the resultant small non-reflective spot will have a negligible effect on the balloon.
  - The Vectran strength element of the balloon laminate material is not affected.
  - The hole itself does not grow because the Teflon layer is acid-resistant.
- Conclusion: acid penetration through small pinholes will not limit balloon lifetime to less than 1 month.